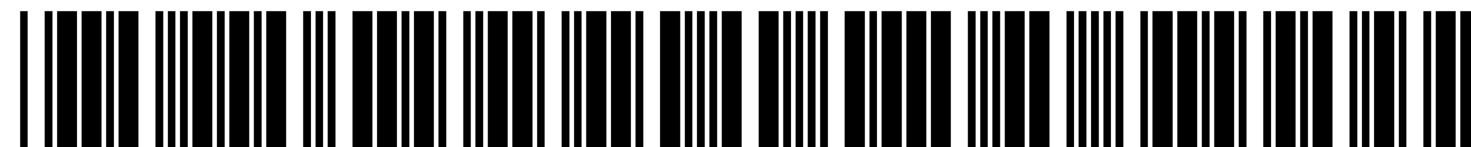

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(45) **Date of Patent: Jan. 24, 2023**

(54) **THERMAL STRUCTURES FOR HEAT TRANSFER DEVICES AND SPATIAL POWER-COMBINING DEVICES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 9 days.

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B33Y 80/00 (2015.01)

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CPC ***H05K 7/209*** (2013.01); ***B33Y 80/00*** (2014.12); *H05K 7/20936* (2013.01)

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See application file for complete search history.

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Primary Examiner — Zachary Pape
Assistant Examiner — Amir A Jalali
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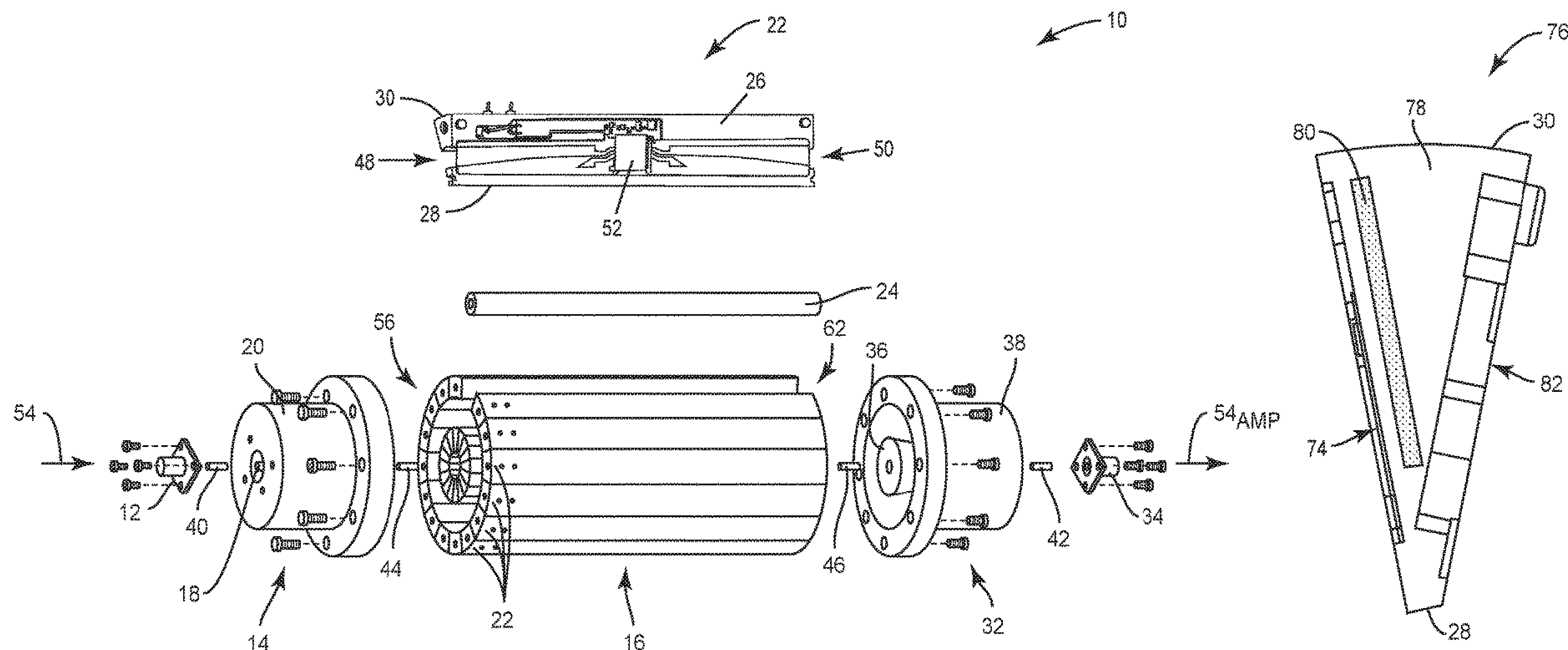
(57) **ABSTRACT**

Thermal structures and, more particularly, improved thermal structures for heat transfer devices and spatial power-combining devices are disclosed. A spatial power-combining device may include a plurality of amplifier assemblies and each amplifier assembly includes a body structure that supports an input antenna structure, an amplifier, and an output antenna structure. One or more heat sinks may be partially or completely embedded within a body structure of such amplifier assemblies to provide effective heat dissipation paths away from amplifiers. Heat sinks may include single-phase or two-phase materials and may include prefabricated complex thermal structures. Embedded heat sinks may be provided by progressively forming unitary body structures around heat sinks by additive manufacturing techniques.

20 Claims, 6 Drawing Sheets



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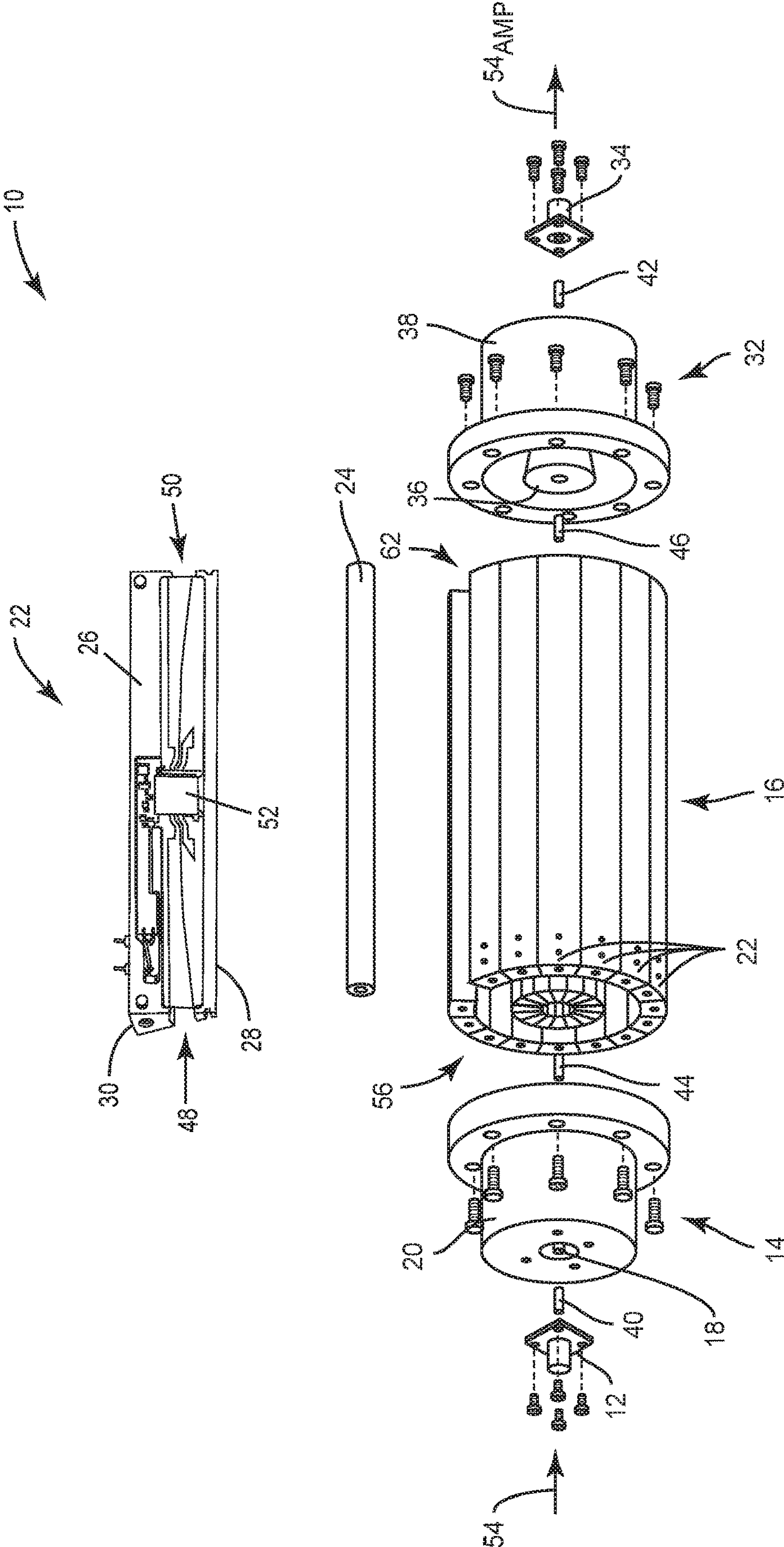

FIG. 1

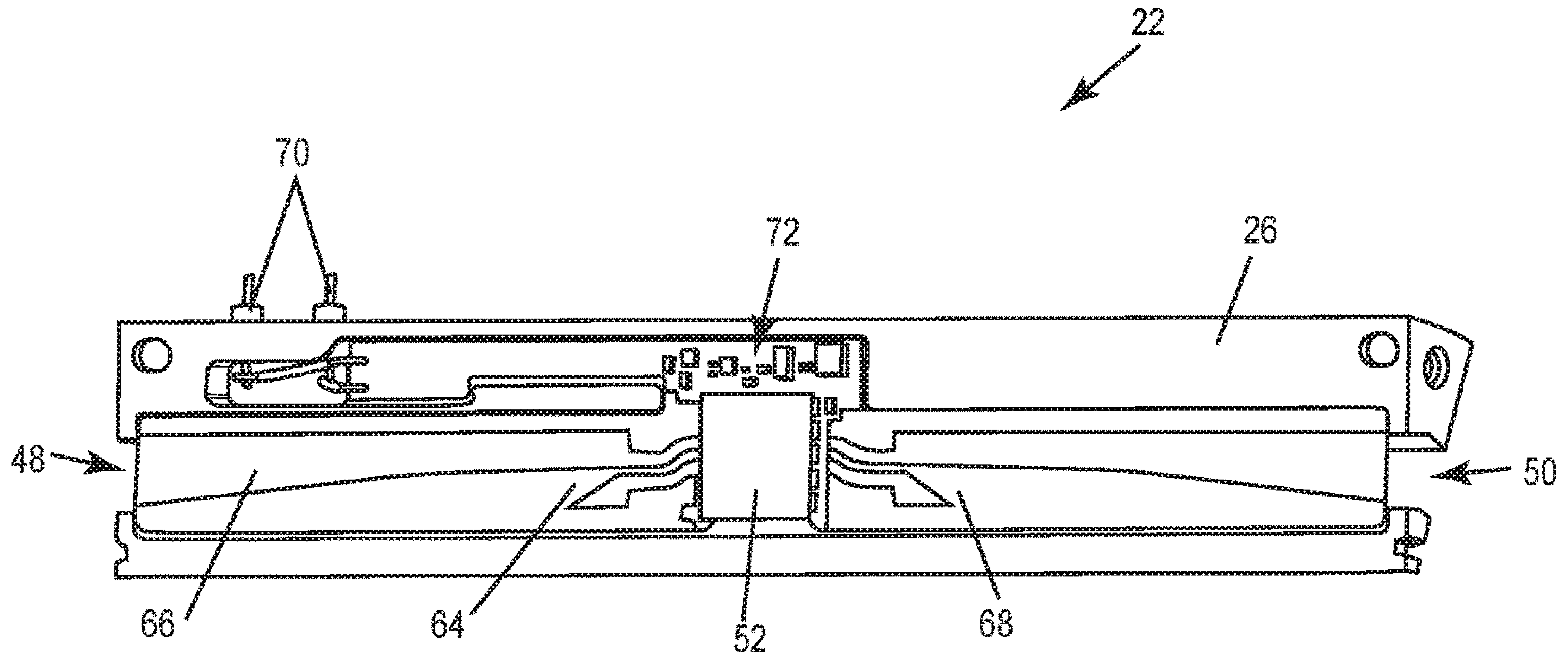

FIG. 2

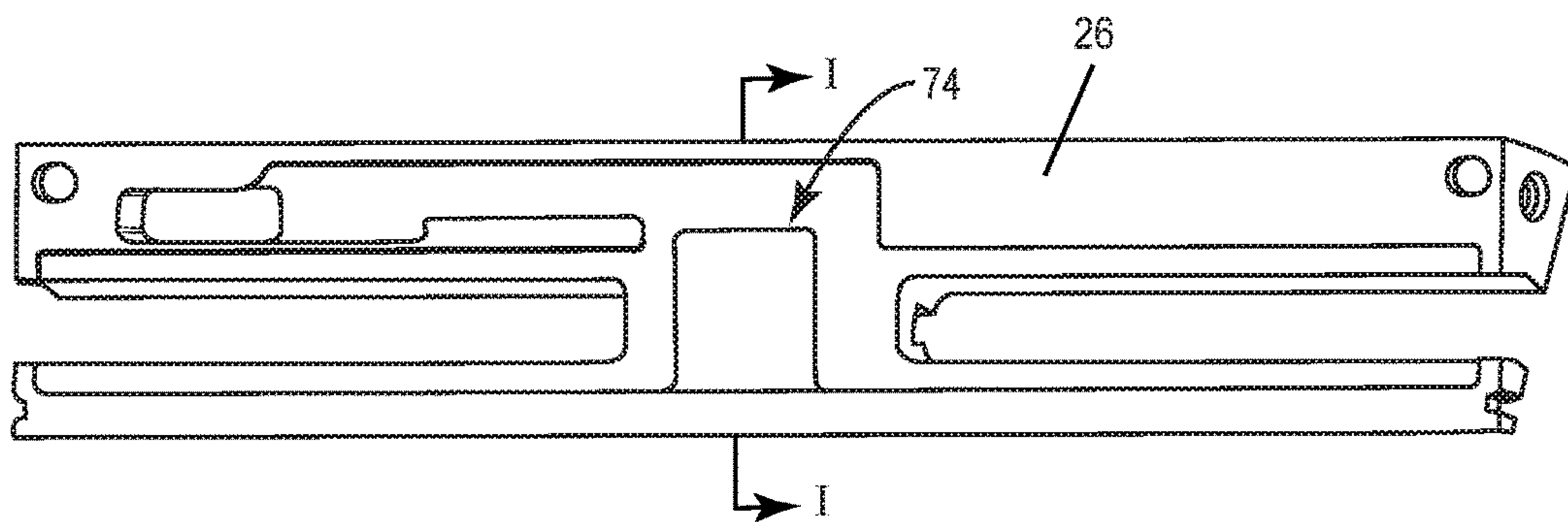

FIG. 3

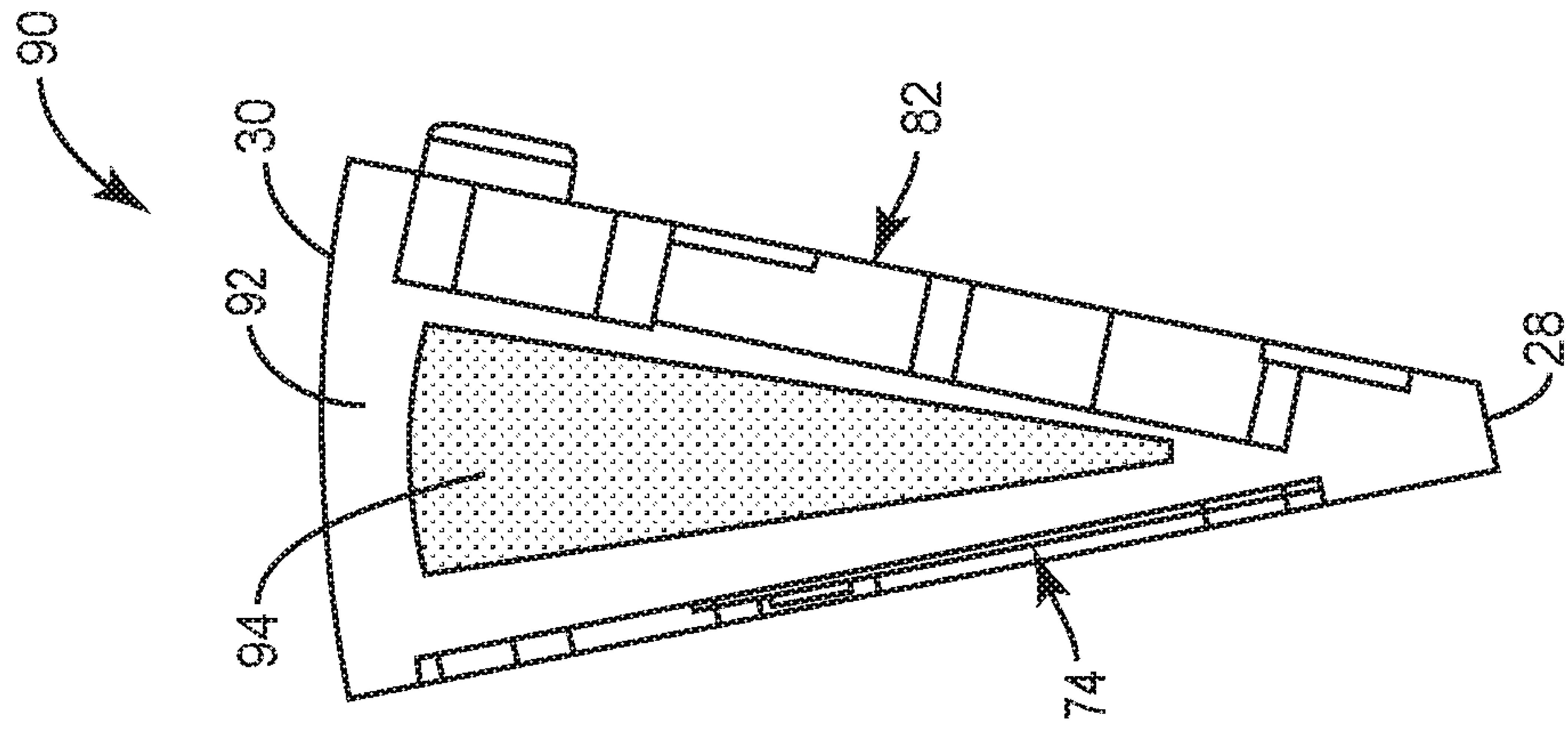

FIG. 6

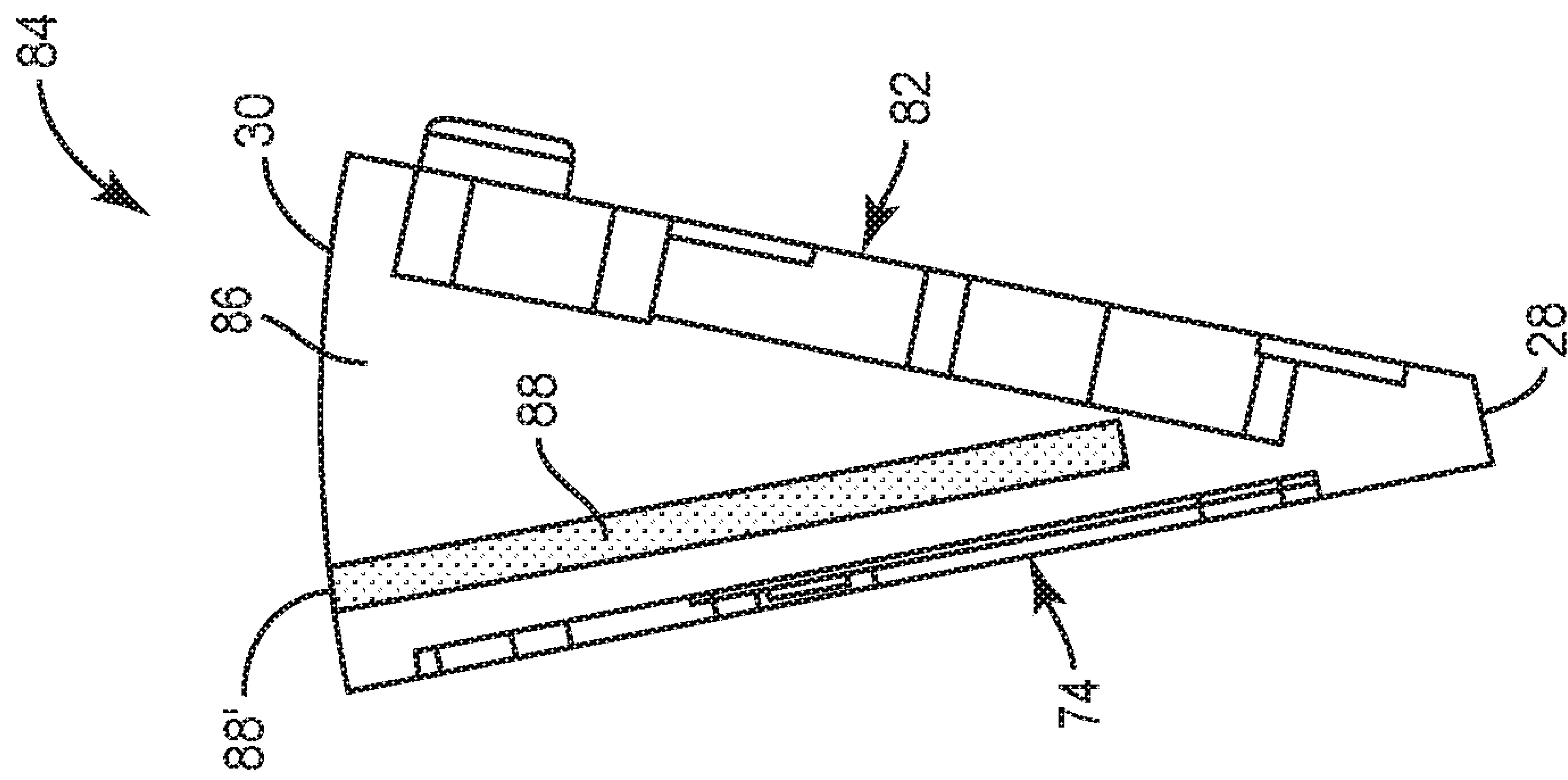

FIG. 5

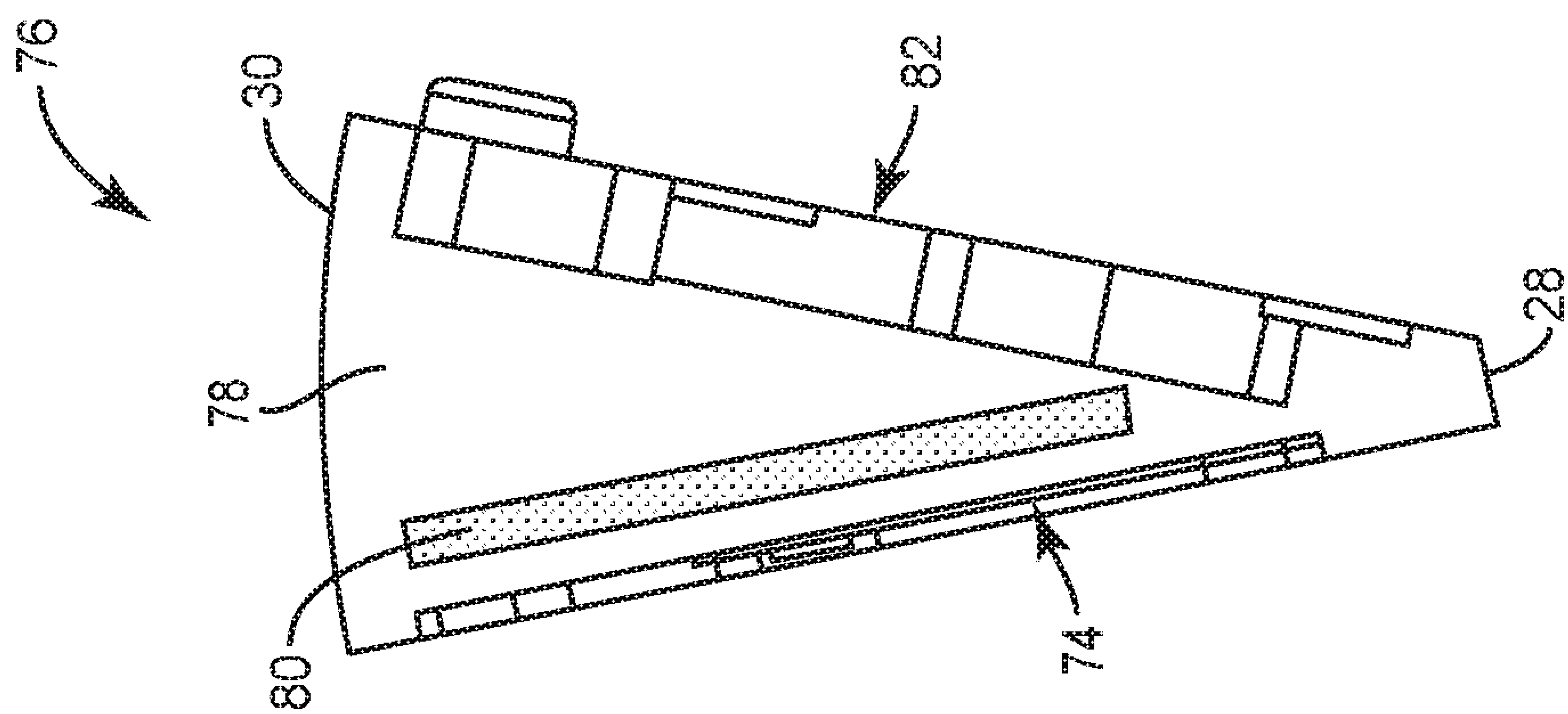

FIG. 4

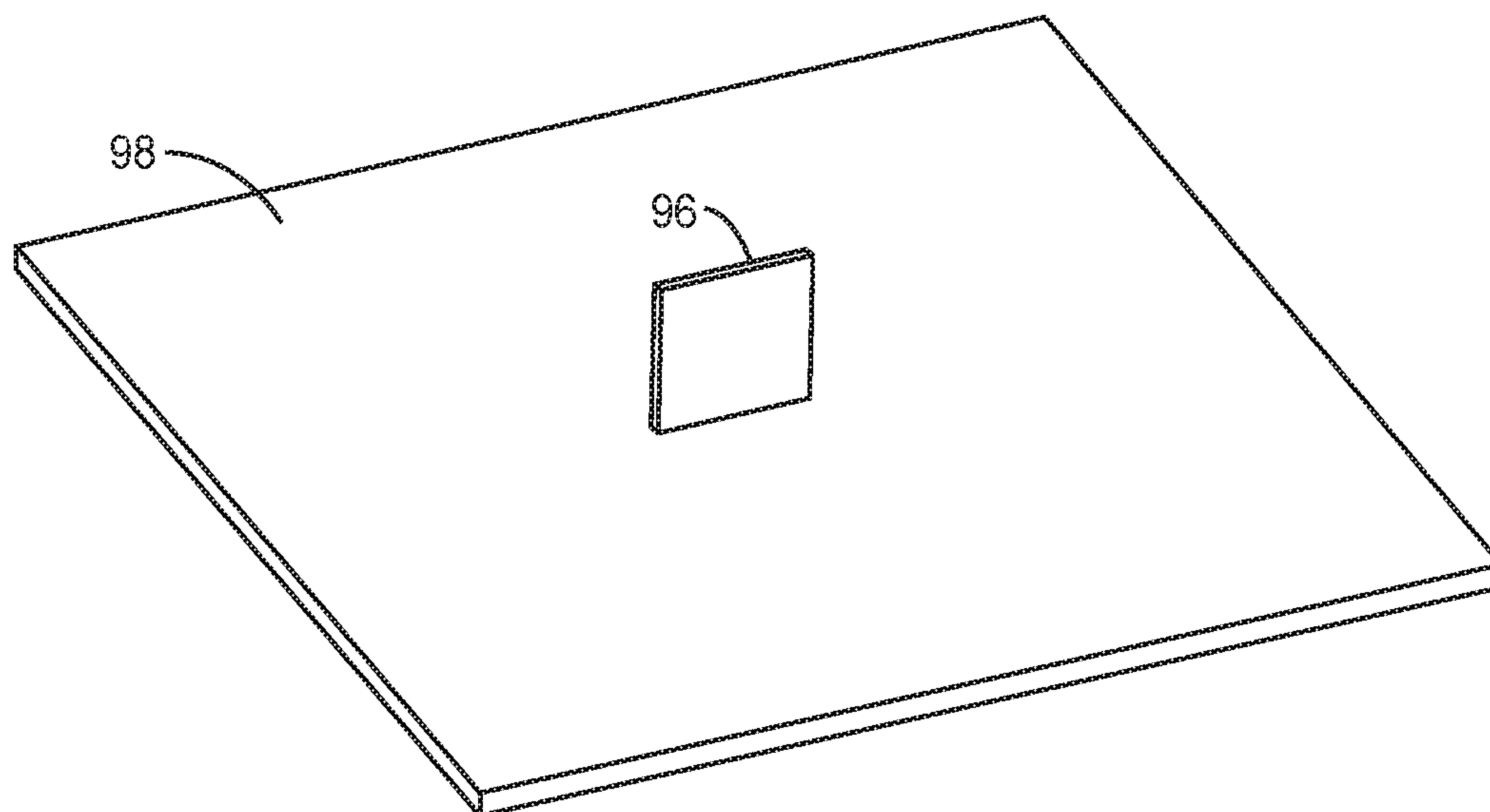

FIG. 7A

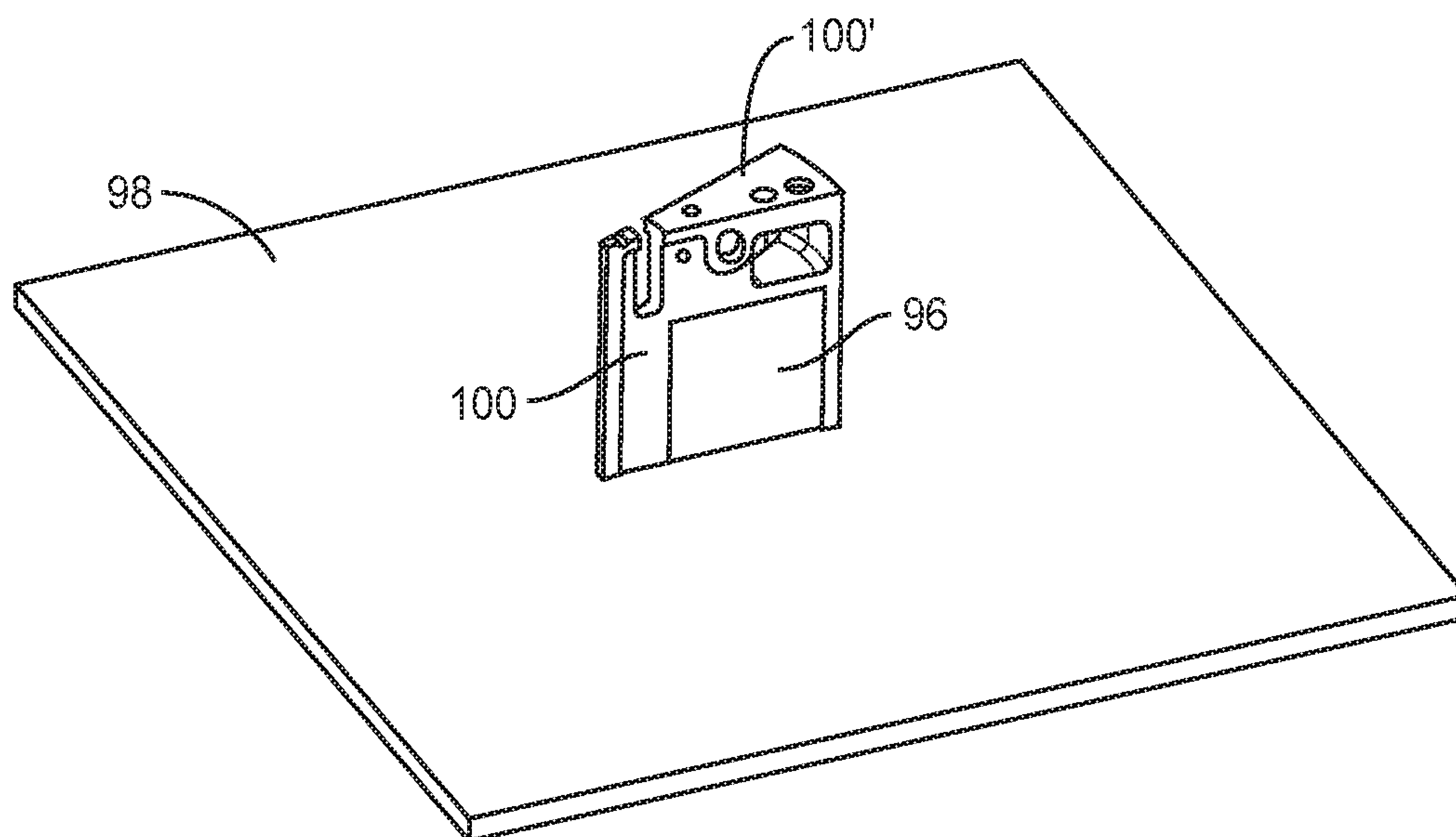

FIG. 7B

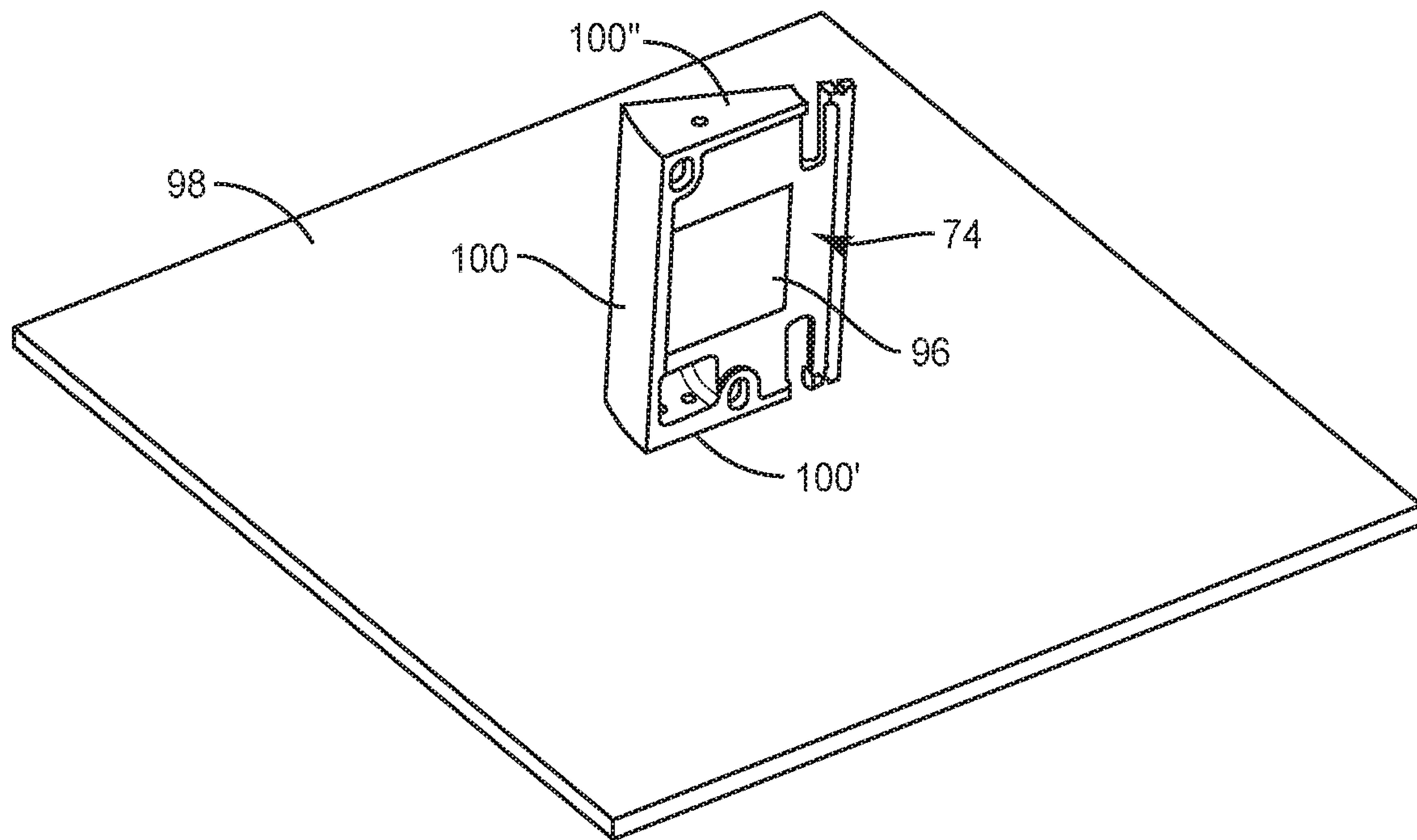

FIG. 7C

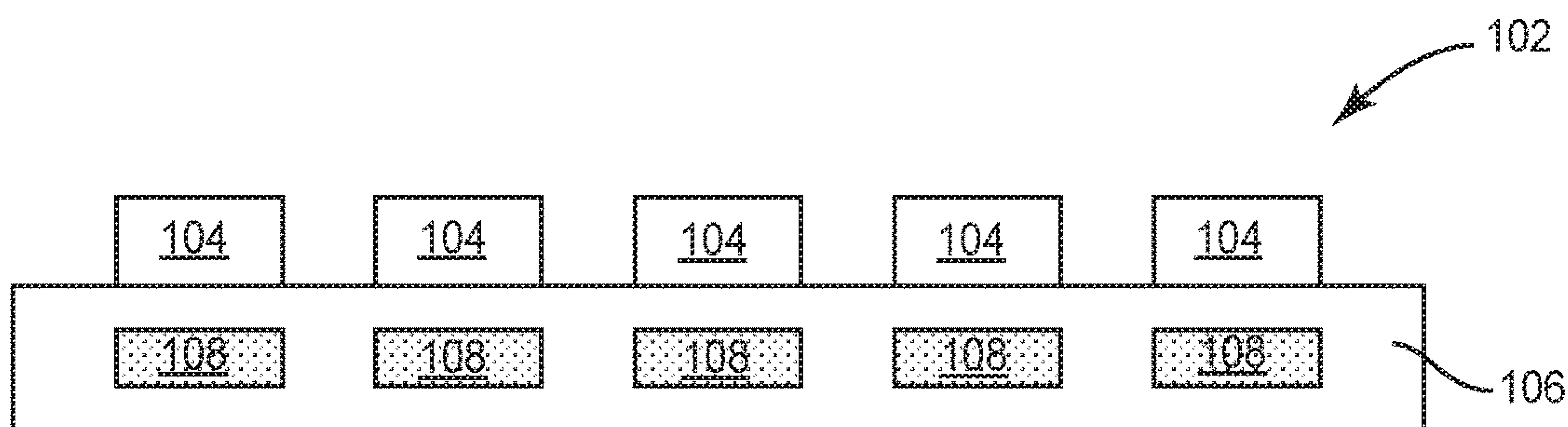

FIG. 8A

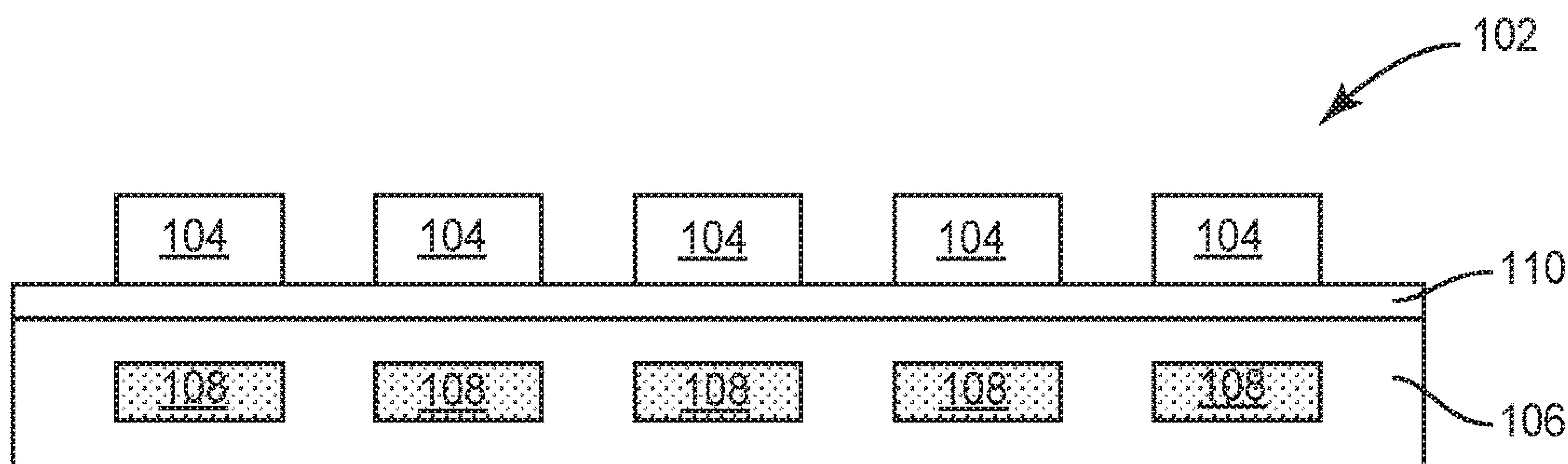

FIG. 8B

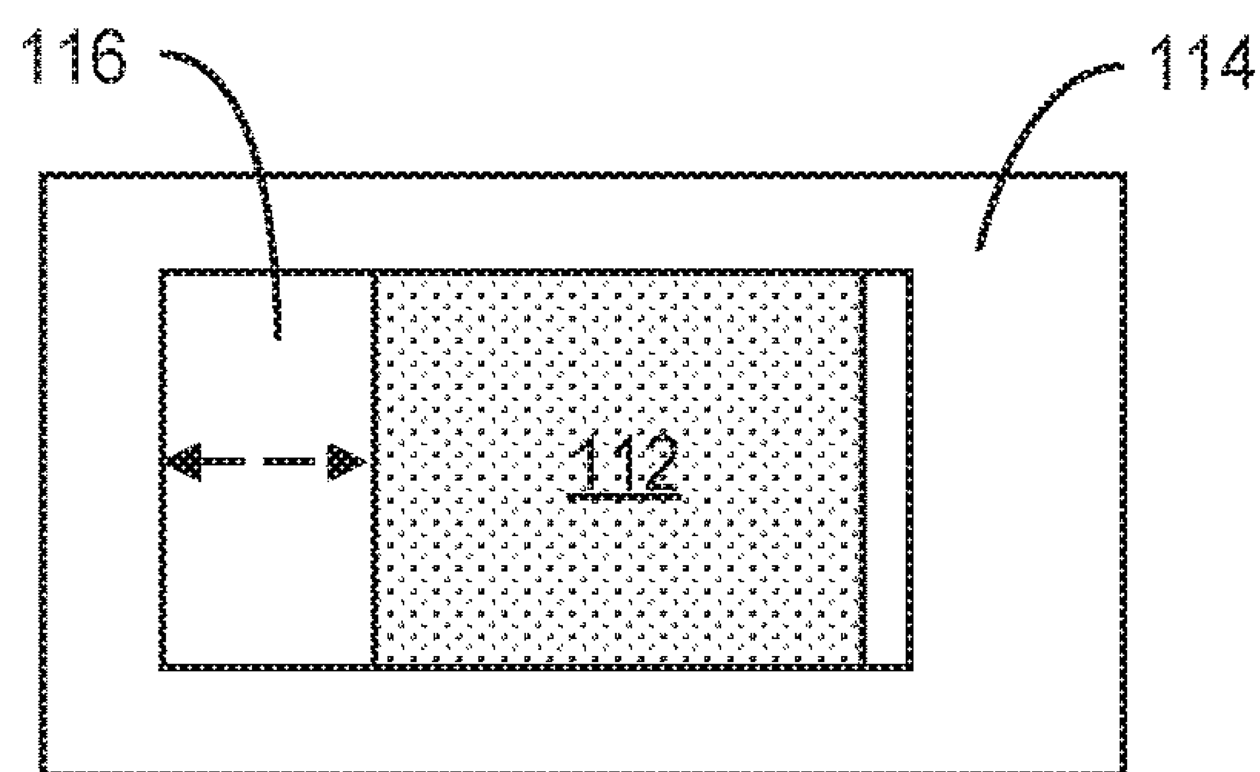

FIG. 9A

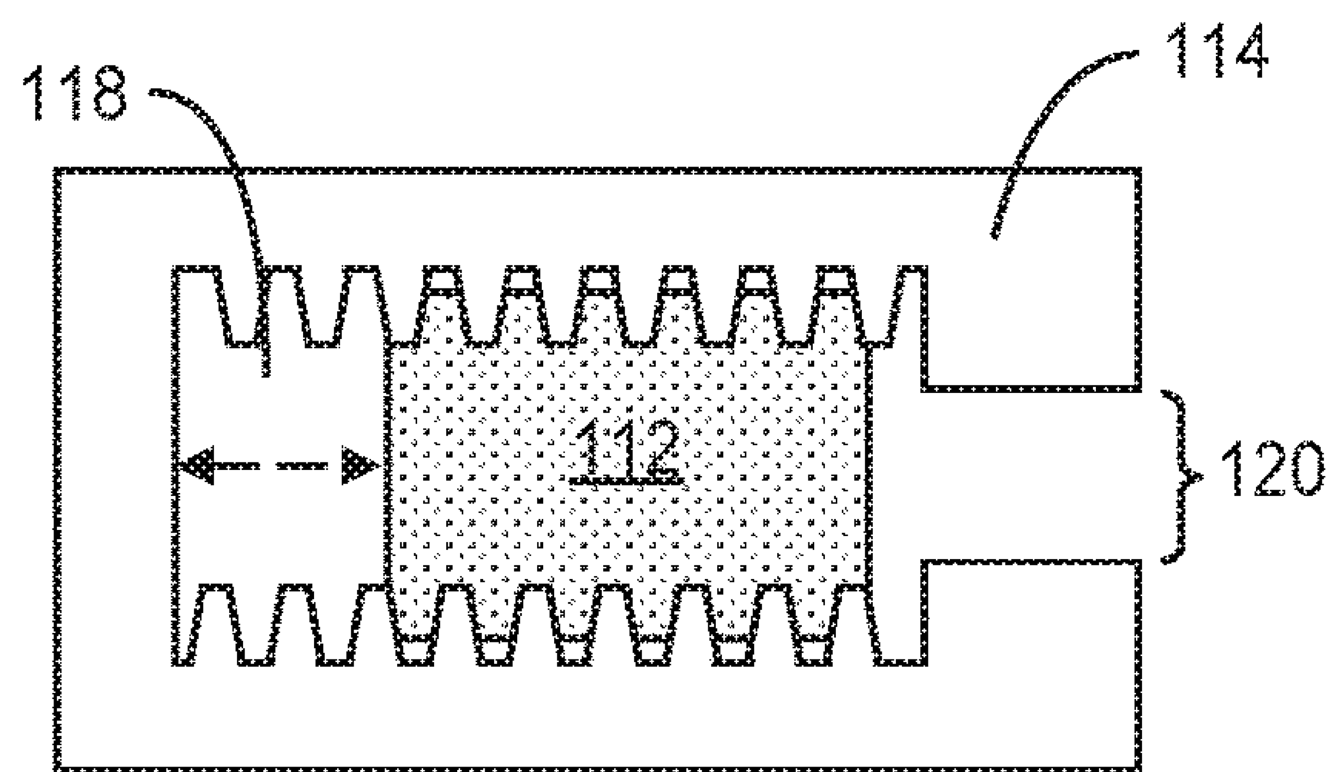

FIG. 9B

THERMAL STRUCTURES FOR HEAT TRANSFER DEVICES AND SPATIAL POWER-COMBINING DEVICES

FIELD OF THE DISCLOSURE

The disclosure relates generally to thermal structures and, more particularly, to improved thermal structures for heat transfer devices and spatial power-combining devices.

BACKGROUND

Spatial power-combining devices are used for broadband radio frequency power amplification in commercial and defense communications, radar, electronic warfare, satellite, and various other communication systems. Spatial power-combining techniques are implemented by combining broadband signals from a number of amplifiers to provide output powers with high efficiencies and operating frequencies. One example of a spatial power-combining device utilizes a plurality of solid-state amplifier assemblies that form a coaxial waveguide to amplify an electromagnetic signal. Each amplifier assembly may include an input antenna structure, an amplifier, and an output antenna structure. When the amplifier assemblies are combined to form the coaxial waveguide, the input antenna structures may form an input antipodal antenna array, and the output antenna structures may form an output antipodal antenna array.

In operation, an electromagnetic signal is passed through an input port to an input coaxial waveguide section of the spatial power-combining device. The input coaxial waveguide section distributes the electromagnetic signal to be split across the input antipodal antenna array. The amplifiers receive the split signals and in turn transmit amplified split signals across the output antipodal antenna array. The output antipodal antenna array and an output coaxial waveguide section combine the amplified split signals to form an amplified electromagnetic signal that is passed to an output port of the spatial power-combining device.

Antenna structures for spatial power-combining devices typically include an antenna signal conductor and an antenna ground conductor deposited on opposite sides of a substrate, such as a printed circuit board. The size of the antenna structures are related to an operating frequency of the spatial power-combining device. For example, the size of the input antenna structure is related to the frequency of energy that can be efficiently received, and the size of the output antenna structure is related to the frequency of energy that can be efficiently transmitted. Overall sizes of spatial power-combining devices typically scale larger or smaller depending on desired operating frequency ranges. Additional size and structural considerations for spatial power-combining devices involve providing good thermal management for heat generated during amplification.

The art continues to seek improved heat transfer devices and spatial power-combining devices having improved mechanical properties and good operating performance while being capable of overcoming challenges associated with conventional devices.

SUMMARY

Aspects disclosed herein relate to thermal structures and, more particularly, to improved thermal structures for heat transfer devices and spatial power-combining devices. A spatial power-combining device may include a plurality of amplifier assemblies and each amplifier assembly includes a body structure that supports an input antenna structure, an amplifier, and an output antenna structure. According to embodiments disclosed herein, one or more heat sinks may be partially or completely embedded within a body structure of such amplifier assemblies to provide effective heat dissipation paths away from amplifiers. Heat sinks may include single-phase or two-phase materials and may include prefabricated complex thermal structures. Embedded heat sinks may be provided by progressively forming unitary body structures around heat sinks by additive manufacturing techniques.

In one aspect, a spatial power-combining device for modifying a signal comprising a plurality of amplifier assemblies, wherein each amplifier assembly of the plurality of amplifier assemblies comprises: an amplifier; a body structure that is configured to support the amplifier; and a heat sink that is entirely embedded within the body structure. In certain embodiments, the heat sink is provided closer to a surface of the body structure that supports the amplifier than an opposing surface of the body structure. In certain embodiments, the heat sink extends within the body structure in a lateral direction relative to a surface of the body structure that supports the amplifier. In certain embodiments, the heat sink extends in the lateral direction a distance that is greater than one or more peripheral edges of the amplifier. In certain embodiments, the heat sink comprises a material having a higher thermal conductivity than the body structure. In certain embodiments, the heat sink comprises one or more of a metal, a ceramic, and a polymer. In certain embodiments, the heat sink comprises one or more of a heat pipe, a thermal ground plane, and a phase change material. In certain embodiments, the heat sink forms two parallel opposing faces within the body structure. In certain embodiments, the heat sink forms a cross-sectional wedge shape. In certain embodiments, the body structure is formed by additive manufacturing.

In another aspect, a spatial power-combining device for modifying a signal comprising a plurality of amplifier assemblies, wherein each amplifier assembly of the plurality of amplifier assemblies comprises: an amplifier; a body structure that is configured to support the amplifier; and a heat sink that is partially embedded within the body structure, the heat sink extending in a lateral direction relative to a surface of the body structure that supports the amplifier a distance that is greater than one or more peripheral edges of the amplifier. In certain embodiments, the heat sink is provided closer to the surface of the body structure that supports the amplifier than an opposing surface of the body structure. In certain embodiments, the heat sink extends in the lateral direction to an outer surface of the body structure such that a peripheral edge of the heat sink is exposed at the outer surface. In certain embodiments, at least a portion of the heat sink is exposed at the surface of the body structure that supports the amplifier. In certain embodiments, the heat sink comprises a material having a higher thermal conductivity than the body structure. In certain embodiments, the heat sink comprises one or more of a metal, a ceramic, and a polymer. In certain embodiments, the heat sink comprises one or more of a heat pipe, a thermal ground plane, and a phase change material. In certain embodiments, the heat sink forms two parallel opposing faces within the body structure. In certain embodiments, the heat sink forms a cross-sectional wedge shape. In certain embodiments, the body structure is formed by additive manufacturing.

In another aspect, any of the foregoing aspects, and/or various separate aspects and features as described herein,

may be combined for additional advantage. Any of the various features and elements as disclosed herein may be combined with one or more other disclosed features and elements unless indicated to the contrary herein.

Those skilled in the art will appreciate the scope of the present disclosure and realize additional aspects thereof after reading the following detailed description of the preferred embodiments in association with the accompanying drawing figures.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

The accompanying drawing figures incorporated in and forming a part of this specification illustrate several aspects of the disclosure, and together with the description serve to explain the principles of the disclosure.

FIG. **1** is a partially-exploded perspective view of a spatial power-combining device.

FIG. **2** is a perspective view of an individual amplifier assembly of the spatial power-combining device of FIG. **1**.

FIG. **3** is a perspective view of a body structure of the amplifier assembly of FIG. **2** with the antenna structures, the amplifier, the ports, and the bias circuitry of FIG. **2** omitted for illustrative purposes.

FIG. **4** represents a cross-section of an amplifier assembly that includes a body structure that is similar to the body structure of FIG. **3** taken along the section line I-I, where the body structure of FIG. **4** further includes an embedded heat sink.

FIG. **5** represents a cross-section of an amplifier assembly that includes a body structure that is similar to the body structure of FIG. **4**, but includes a partially embedded heat sink.

FIG. **6** represents a cross-section of an amplifier assembly that includes a body structure that is similar to the body structure of FIG. **4**, but includes a heat sink that forms a cross-sectional shape that corresponds to a cross-sectional shape of the amplifier assembly.

FIGS. **7**A-**7**C illustrated steps for fabricating an amplifier assembly with an embedded heat sink according to additive manufacturing steps as disclosed herein.

FIGS. **8**A and **8**B are cross-sectional illustrations of a planar power amplifier device that includes one or more amplifiers mounted on a substrate that includes one or more embedded heatsinks.

FIGS. **9**A and **9**B are cross-sectional views of exemplary structures where a first object is embedded and movable within a second object that is formed by additive manufacturing.

DETAILED DESCRIPTION

The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.

It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present disclosure. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items.

It will be understood that when an element such as a layer, region, or substrate is referred to as being "on" or extending "onto" another element, it can be directly on or extend directly onto the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly on" or extending "directly onto" another element, there are no intervening elements present. Likewise, it will be understood that when an element such as a layer, region, or substrate is referred to as being "over" or extending "over" another element, it can be directly over or extend directly over the other element or intervening elements may also be present. In contrast, when an element is referred to as being "directly over" or extending "directly over" another element, there are no intervening elements present. It will also be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

Embodiments are described herein with reference to schematic illustrations of embodiments of the disclosure. As such, the actual dimensions of the layers and elements can be different, and variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are expected. For example, a region illustrated or described as square or rectangular can have rounded or curved features, and regions shown as straight lines may have some irregularity. Thus, the regions illustrated in the figures are schematic and their shapes are not intended to illustrate the precise shape of a region of a device and are not intended to limit the scope of the disclosure. Common elements between figures may be shown herein with common element numbers and may not be subsequently re-described.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context

of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Aspects disclosed herein relate to thermal structures and, more particularly, to improved thermal structures for heat transfer devices and spatial power-combining devices. A spatial power-combining device includes a plurality of amplifier assemblies and each amplifier assembly includes a body structure that supports an input antenna structure, an amplifier, and an output antenna structure. According to embodiments disclosed herein, one or more heat sinks may be partially or completely embedded within a body structure of such amplifier assemblies to provide effective heat dissipation paths away from amplifiers. Heat sinks may include single-phase or two-phase materials and may include prefabricated complex thermal structures. Embedded heat sinks may be provided by progressively forming unitary body structures around heat sinks by additive manufacturing techniques.

FIG. **1** is a partially-exploded perspective view of a spatial power-combining device **10**. The spatial power-combining device **10** comprises an input port **12** and an input coaxial waveguide section **14**. The input coaxial waveguide section **14** provides a broadband transition from the input port **12** to a center waveguide section **16**. Electrically, the input coaxial waveguide section **14** provides broadband impedance matching from an impedance Z_{p1} of the input port **12** to an impedance Z_c of the center waveguide section **16**. The input coaxial waveguide section **14** includes an inner conductor **18** and an outer conductor **20** that radially surrounds the inner conductor **18**, thereby forming an opening therebetween. Outer surfaces of the inner conductor **18** and an inner surface of the outer conductor **20** have gradually changed profiles configured to minimize the impedance mismatch from the input port **12** to the center waveguide section **16**.

The center waveguide section **16** comprises a plurality of amplifier assemblies **22** arranged radially around a center axis of the spatial power-combining device **10**. In certain embodiments, a center post **24** is provided at the center axis for mechanical support and the plurality of amplifier assemblies **22** may be positioned circumferentially around the center post **24**. In other embodiments, the center post **24** may be omitted. In FIG. **1**, the center post **24** is illustrated in an exploded manner. Each amplifier assembly **22** comprises a body structure **26** having a predetermined wedge-shaped cross-section, an inner surface **28**, and an arcuate outer surface **30**. When the amplifier assemblies **22** are collectively assembled radially about the center axis, they form the center waveguide section **16** with a generally cylindrical shape; however, other shapes are possible, such as rectangular, oval, or other geometric shapes.

The spatial power-combining device **10** also comprises an output coaxial waveguide section **32** and an output port **34**. The input port **12** and the output port **34** may comprise any of a field-replaceable Subminiature A (SMA) connector, a super SMA connector, a type N connector, a type K connector, a WR28 connector, other coaxial to waveguide transition connectors, or any other suitable coaxial or waveguide connectors. In embodiments where the operating frequency range includes a frequency of at least 18 gigahertz (GHz), the output port **34** may comprise a waveguide output port, such as a WR28 or other sized waveguide. The output coaxial waveguide section **32** provides a broadband transition from the center waveguide section **16** to the output port **34**. Electrically, the output coaxial waveguide section **32** provides broadband impedance matching from the impedance Z_c of the center waveguide section **16** to an impedance Z_{p2} of the output port **34**. The output coaxial waveguide section **32** includes an inner conductor **36** and an outer conductor **38** that radially surrounds the inner conductor **36**, thereby forming an opening therebetween. Outer surfaces of the inner conductor **36** and an inner surface of the outer conductor **38** have gradually changed profiles configured to minimize the impedance mismatch from the output port **34** to the center waveguide section **16**. In certain embodiments, a pin **40** connects between the input port **12** and the input coaxial waveguide section **14**, and a pin **42** connects between the output port **34** and the output coaxial waveguide section **32**. In certain embodiments, the center post **24** connects with the inner conductors **18**, **36** by way of screws **44**, **46** on opposite ends of the center post **24**. The center post **24** is provided for simplifying mechanical connections, may have other than a cylindrical shape, and may be omitted altogether.

Each amplifier assembly **22** comprises an input antenna structure **48** and an output antenna structure **50**, both of which are coupled to an amplifier **52**. In some embodiments, the amplifier **52** comprises a monolithic microwave integrated circuit (MMIC) amplifier. A MMIC may be a solid-state gallium nitride (GaN)-based MMIC. A GaN MMIC device provides high power density and bandwidth, and a spatial power-combining device may combine power from a plurality of GaN MMICs efficiently in a single step to minimize combining loss.

In operation, an input signal **54** is propagated from the input port **12** to the input coaxial waveguide section **14**, where it radiates between the inner conductor **18** and the outer conductor **20** and concurrently provides the input signal **54** to the center waveguide section **16**. The input antenna structures **48** of the plurality of amplifier assemblies **22** collectively form an input antenna array **56**. The input antenna array **56** couples the input signal **54** from the input coaxial waveguide section **14**, distributing the input signal **54** substantially evenly to each one of the amplifier assemblies **22**. Each input antenna structure **48** receives a signal portion of the input signal **54** and communicates the signal portion to the amplifier **52**. The amplifier **52** amplifies the signal portion of the input signal **54** to generate an amplified signal portion that is then transmitted from the amplifier **52** to the output antenna structure **50**. The output antenna structures **50** collectively form an output antenna array **62** that operates to provide the amplified signal portions to be concurrently combined inside the opening of the output coaxial waveguide section **32** to form an amplified output signal $\mathbf{54}_{AMP}$, which is then propagated through the output coaxial waveguide section **32** to the output port **34**.

FIG. **2** is a perspective view of an individual amplifier assembly **22** of FIG. **1** according to embodiments disclosed herein. The input antenna structure **48** comprises an input signal conductor **64** supported on a first face of a substrate **66** or board, and the output antenna structure **50** comprises an output signal conductor **68** that is also supported on the first face of the substrate **66**. The input signal conductor **64** and the output signal conductor **68** are electromagnetically coupled to the amplifier **52**. The substrate **66** may be a printed circuit board that provides a desired form factor and mechanical support for the input signal conductor **64** and the output signal conductor **68**. The input antenna structure **48** also includes an input ground conductor (not visible) on an opposing second face of the substrate **66** to the input signal conductor **64**. In a similar manner, the output antenna structure **50** includes an output ground conductor (not visible) on the opposing second face of the substrate **66** to the output signal conductor **68**. In other embodiments, the

substrate **66** may be substituted with a plurality of substrates or boards. In still other embodiments, the input signal conductor **64**, the input ground conductor (not visible), the output signal conductor **68**, and the output ground conductor (not visible) are mechanically supported by the body structure **26** such that the substrate **66** may not be present. In certain embodiments, one or more ports **70** are provided for an external voltage input, such as from a direct current voltage source, and corresponding bias circuitry **72** is provided to control the amplifier **52**. In certain embodiments, the bias circuitry **72** is arranged on the same substrate **66** as the antenna structures **48**, **50**. In other embodiments, a separate substrate may be provided for the bias circuitry **72**.

In operation, a portion of the input signal (**54** in FIG. **1**) is received by the input antenna structure **48** where it radiates between the input signal conductor **64** and the input ground conductor (not visible) and propagates to the amplifier **52** for amplification. For embodiments with a board **66**, the portion of the input signal (**54** in FIG. **1**) radiates between the input signal conductor **64** and the input ground conductor (not visible) through the board **66**. For embodiments without a board **66**, the portion of the input signal (**54** in FIG. **1**) radiates between the input signal conductor **64** and the input ground conductor (not visible) through air. The amplifier **52** outputs a portion of the amplified signal ($\mathbf{54}_{AMP}$ in FIG. **1**) to the output antenna structure **50** where it radiates between the output signal conductor **68** and the output ground conductor (not visible) in a similar manner.

Turning back to FIG. **1**, the spatial power-combining device **10** is typically utilized for high power-combining applications. Accordingly, the amplifier **52** in each of the amplifier assemblies **22** is configured for high power amplification, and may therefore generate a high amount of heat. If the operating temperature of each amplifier **52** increases too much, the performance and lifetime of each amplifier **52** may suffer. As previously described, the plurality of amplifier assemblies **22** form the center waveguide section **16**. In this regard, thermal management is needed to effectively dissipate heat in and around the center waveguide section **16**. Accordingly, the body structure **26** of each amplifier assembly **22** may typically comprise a thermally conductive material, such as copper (Cu), aluminum (Al), or alloys thereof that are configured to dissipate enough heat from the amplifier **52** to maintain a suitably low operating temperature. In certain applications, the body structure **26** may comprise graphite with an electrically conductive film, such as nickel (Ni), Cu, or combinations thereof.

FIG. **3** is a perspective view of the body structure **26** of FIG. **2** with the antenna structures **48**, **50**, the amplifier **52**, the ports **70**, and the bias circuitry **72** of FIG. **2** omitted for illustrative purposes. The body structure **26** includes a surface **74** on which an amplifier will be mounted or otherwise arranged. As previously described, during operation, amplifiers generate heat within amplifier assemblies of spatial power-combining devices. In this manner, the surface **74** is arranged in closest proximity to a heat generating amplifier after assembly.

According to aspects disclosed herein, body structures of amplifier assemblies for spatial power-combining devices may include one or more heat sinks that are partially or fully embedded within the body structures. The heat sinks may be arranged in proximity to heat-generating amplifiers to provide effective heat dissipation paths away from such amplifiers. In certain embodiments, the heat sinks are formed with a higher thermal conductivity than a material that forms the body structures. In certain embodiments, the heat sinks may comprise single-phase heat sinks and/or two-phase heat sinks. In certain embodiments, heat sinks may comprise one or more of a solid metal, ceramic, graphite, or polymer materials and combinations thereof. For example, an exemplary amplifier assembly may comprise a copper or graphite heat sink that is embedded within an aluminum body structure. In certain embodiments, heat sinks may comprise pre-fabricated complex objects such heat pipes, thermal ground planes (TGP), and phase change materials such as paraffin wax.

In order to either partially or fully embed such heat sinks within heat transfer devices and/or body structures of amplifier assemblies, additive manufacturing techniques such as three-dimensional (3-D) printing may be employed. Additive manufacturing may include forming structures in a layer-by-layer manner using source materials of powders, wires, and/or sheets of materials. For example, a structure may be formed by employing focused energy such as an electron beam or a laser beam to selectively melt and/or sinter powder to progressively form the structure. A structure formed by additive manufacturing typically includes unique properties due to the progressive nature of the process. For example, the microstructure of metals formed by additive manufacturing have unique structures compared with conventionally formed metals. In particular, columnar grain structures may predominately form with high quantities of grain orientation. With subsequent heating and cooling cycles, some axial variation of grain structures and material phases may also occur. In this regard, a heat transfer device may be formed by progressively forming a carrier, substrate, or body structure around one or more heat sinks. For spatial power-combining devices, a body structure may be progressively formed around a heat sink, thereby providing an amplifier assembly with an embedded heat sink. As such, a body structure that is formed by additive manufacturing comprises a particular structure that may not be achievable by conventional techniques such as machining, forging, and casting. In particular, the body structure may be formed with a seamless structure around the heat sink as opposed to conventional techniques that may join different halves together, thereby introducing seams that can provide mechanical and electrical failure points for an assembled spatial power-combining device. Accordingly, the body structure formed by additive manufacturing may comprise a unitary structure around the heat sink. Additionally, the heat sinks may be provided without mechanically removing portions of a body structure, such as drilling into the body structure to form one or more thermal vias.

FIG. **4** represents a cross-section of an amplifier assembly **76** that includes a body structure **78** that is similar to the body structure **26** taken along the section line I-I of FIG. **3**, where the body structure **78** further includes an embedded heat sink **80**. In FIG. **4**, the heat sink **80** is entirely embedded within the body structure **78** such that no portions of the heat sink **80** are exposed outside of the body structure **78**. The heat sink **80** may be provided within the body structure **78** in a location that is closer to the surface **74** on which an amplifier will be mounted than an opposing surface **82** that will be arranged closer to an amplifier of an adjacent amplifier assembly in a fully assembled spatial power-combining device. In certain embodiments, the heat sink **80** may extend farther in a longitudinal direction from the inner surface **28** to the outer surface **30** of the body structure **78**, rather than across the body structure **78**. In this manner, the heat sink **80** may provide a heat path that effectively dissipates heat in a direction that is lateral to the surface **74** on which an amplifier is mounted. In certain embodiments, the heat sink **80** may extend within the body structure **78** in

lateral directions that are greater than one or more peripheral edges of an amplifier mounted on the surface **74**. As previously described, the heat sink **80** may comprise one or more of thermally conductive materials or elements including a solid metal, a ceramic material, a graphite material, a polymer material, and pre-fabricated complex objects such heat pipes, TGPs, and phase change materials. While a single heat sink **80** is illustrated, the amplifier assembly **76** may comprise a plurality of heat sinks **80** that are entirely embedded within the body structure **86**.

FIG. **5** represents a cross-section of an amplifier assembly **84** that includes a body structure **86** that is similar to the body structure **78** of FIG. **4**, but includes a partially embedded heat sink **88**. In FIG. **5**, a peripheral edge **88'** of the heat sink **88** is exposed at the outer surface **30** of the body structure **86**. In this manner, heat from an amplifier mounted on the surface **74** may dissipate along a lateral path that extends to the peripheral edge **88'** and outside of the body structure **86**. In certain embodiments, an external heat transfer device may be provided proximate to the outer surface **30** of the amplifier assembly **84**. For example, when a plurality of the amplifier assemblies **84** are radially arranged to form a center waveguide section (**16** of FIG. **1**), an external heat transfer device may be formed around the center waveguide section proximate to the outer surface **30** of each amplifier assembly **84**. In this regard, the heat sink **88** may be thermally coupled to the external heat transfer device without portions of the body structure **86** being provided between the outer surface **30** and the heat sink **88**. In further embodiments, one or more portions of the heat sink **88** may be exposed at other surfaces of the body structure **86**. For example, a portion of the heat sink **88** may be exposed at the surface **74** on which an amplifier is mounted. In this regard, an amplifier may be mounted to the heat sink **88** without portions of the body structure **86** being provided between the amplifier and the heat sink **88**, thereby forming a heat dissipation path from the amplifier to the heat sink **88** that is devoid of any portion of the body structure **86**. While the heat sink **88** (and the heat sink **80** of FIG. **4**) is illustrated with a cross-sectional shape that forms generally parallel opposing faces within the body structure **86**, other shapes are possible. The heat sink **88** may comprise any of the materials described above for the heat sink **80** of FIG. **4**. Additionally, while a single heat sink **88** is illustrated, the amplifier assembly **84** may comprise a plurality of heat sinks **88** that are partially embedded within the body structure **86**.

FIG. **6** represents a cross-section of an amplifier assembly **90** that includes a body structure **92** that is similar to the body structure **78** of FIG. **4**, but includes a heat sink **94** that forms a cross-sectional shape that corresponds to a cross-sectional shape of the amplifier assembly **90**. As previously described, the amplifier assembly **90** may form a cross-sectional wedge shape for radial assembly within a spatial power-combining device. In FIG. **6**, the heat sink **94** also forms a cross-sectional wedge shape. In this regard, the heat sink **94** may be formed with increased volume within the body structure **92** to provide further heat dissipation capabilities. While the heat sink **94** is illustrated as entirely embedded within the body structure **92**, the heat sink **94** may also be partially embedded in any of the configurations described for the heat sink **88** of FIG. **5**. Additionally, the heat sink **94** may comprise any of the materials described above and the amplifier assembly **90** may comprise a plurality of the heat sinks **94** without deviated from the principles disclosed herein.

FIGS. **7A-7C** illustrated steps for fabricating an amplifier assembly with an embedded heat sink according to additive manufacturing steps as disclosed herein. In FIG. **7A**, a heat sink **96** is provided on a support surface **98** or table. The heat sink **96** may comprise any of the previously described thermally conductive materials or elements, including metal materials, ceramic materials, graphite materials, polymer materials, and pre-fabricated complex objects such heat pipes, TGPs, and phase change materials.

In FIG. **7B**, a portion of a body structure **100** is formed around the heat sink **96** by additive manufacturing. As previously described, the body structure **100** may comprise a thermally conductive metal such as Cu, Al, or alloys thereof. In this regard, a metal additive manufacturing process such as direct metal laser sintering (DMLS) may be employed. As such, the body structure **100** may be formed by laser sintering fine metal powders to progressively build up the body structure **100** from the support surface **98**. In FIG. **7B**, the body structure **100** is partially formed around the heat sink **96** until a first end **100'** of the body structure **100** is completed opposite the support surface **98**. As illustrated in FIG. **7C**, the body structure **100** and the heat sink **96** may then be separated from the support surface **98** and subsequently flipped over to place the first end **100'** on the support surface **98**. The remainder of the body structure **100** may then be formed by additive manufacturing until a second end **100"** of the body structure that is opposite the first end **100'** is fully formed. After completion, the body structure **100** with the embedded heat sink **96** may be removed from the table to form an amplifier assembly as previously described.

In FIG. **7C**, the heat sink **96** is illustrated as partially embedded in the body structure **100** such that a portion of the heat sink **96** is exposed at the surface **74** of the body structure **100** where an amplifier will be mounted. In certain embodiments, lateral dimensions of the exposed portion of the heat sink **96** relative to the surface **74** are arranged at least the same as lateral dimensions of an amplifier that will be mounted to promote improved thermal coupling. In further embodiments, lateral dimensions of the exposed portion of the heat sink **96** may extend past peripheral edges of an amplifier that will be mounted. While the heat sink **96** is illustrated as partially embedded, the heat sink **96** may alternatively be entirely embedded within the body structure as previously described. By forming the body structure **100** by additive manufacturing, the heat sink **96** may comprise large and/or complex shapes and structures embedded within the body structure **100**. In certain embodiments, the additive manufacturing of the body structure **100** may include other additive manufacturing techniques, such as selective laser melting (SLM), laser cladding, laser metal deposition, and electron beam melting.

While the above described embodiments are related to spatial power-combining devices, aspects described herein are applicable to other heat transfer devices and structures. FIG. **8A** is a cross-sectional illustration of a planar power amplifier device **102** that includes one or more amplifiers **104** mounted on a planar thermal structure **106** that includes one or more embedded heatsinks **108**. The planar thermal structure **106** may comprise a substrate, a carrier, or the like that is configured to support the one or more amplifiers **104**. In certain embodiments, the power amplifier device **102** comprises a solid state power amplifier (SSPA) device. As illustrated, the amplifiers **104** may be mounted on the planar thermal structure **106** in positions that are registered with the heatsinks **108**. In certain embodiments, the planar thermal structure **106** may be formed around the heatsinks **108** by additive manufacturing techniques as described above such that the heat sinks **108** may be partially or fully embedded

within the planar thermal structure **106**. For such applications, the planar thermal structure **106** may comprise a solid material formed by additive manufacturing, and the heatsinks **108** may comprise solid materials or pre-fabricated complex objects such as heat pipes, TGPs, and phase change materials. In certain embodiments, the planar thermal structure **106** with embedded heatsinks **108** may be provided to replace one or more conventional cold plates in planar applications. For such embodiments, the planar thermal structure **106** may form an improved or hybrid cold plate with embedded heatsinks **108**. For example, the planar thermal structure **106** may be formed by additive manufacturing to include one or more fluid channels in regions separate from the embedded heatsinks **108**. The fluid channels may form conduits for flow of cooling liquids, gels, and/or gases that, in combination with the heatsinks **108**, provide improved heat transfer for the power amplifier device **102**. As illustrated in FIG. **8**B, the power amplifier device **102** may further comprise at least one additional layer **110** formed between the amplifiers **104** and the planar thermal structure **106**. The additional layer **110** may comprise electrical traces for the amplifiers **104**, a printed circuit board, and one or more dielectric materials. In certain embodiments, the at least one additional layer **110** may comprise an additional heat sink including a cold plate, among others, that promotes additional thermal dissipation in combination with the planar thermal structure **106** with embedded heatsinks **108**.

As described herein, additive manufacturing techniques are described that either partially or fully embed one object within another object. Such additive manufacturing techniques may be applicable to form metal materials around one or more embedded objects. Additionally, the embedded objects may also comprise metal materials, other thermally conductive materials, and/or complex pre-fabricated objects as described above. In certain embodiments, the embedded object may be formed to be movable within the other object. For example, FIGS. **9**A and **9**B are cross-sectional views of exemplary structures where a first object **112** is embedded and movable within a second object **114**. In FIG. **9**A, the second object **114** may be formed in a unitary manner by additive manufacturing around the first object **112** such that a cavity **116** or opening is formed around the first object **112**. The cavity **116** may be formed with a relative size that is larger in at least one dimension than the first object **112**. In this regard, a position of the first object **112** within the second object **114** may be adjustable in at least one direction as indicated by the dashed-line arrow within the cavity **116**. In FIG. **9**B, the first object **112** and the second object **114** may form more complex shapes. As illustrated, the first object **112** may form a threaded insert such as a screw or a bolt that is embedded within the second object **114**. As such, the second object **114** may be formed by additive manufacturing and may further include a corresponding threaded cavity **118**. As illustrated, the first object **112** may be accessible through an opening **120** formed in the second object **114**. In this manner, a position of the first object **112** may be moved within the second object **114** as indicated by the dashed-line arrow within the threaded cavity **118**. In certain embodiments, the first object **112** may comprise a heat sink as described above and the second object **114** may comprise a body structure as described above. The ability to re-position a heat sink within a body structure may be beneficial for tuning, adjusting, and/or optimizing heat dissipation paths within power amplifier structures.

In certain embodiments, any of the foregoing aspects, and/or various separate aspects and features as described herein, may be combined for additional advantage. Any of the various features and elements as disclosed herein may be combined with one or more other disclosed features and elements unless indicated to the contrary herein.

Those skilled in the art will recognize improvements and modifications to the preferred embodiments of the present disclosure. All such improvements and modifications are considered within the scope of the concepts disclosed herein and the claims that follow.

What is claimed is:

1. A spatial power-combining device for modifying a signal comprising a plurality of amplifier assemblies radially arranged around a center axis, wherein each amplifier assembly of the plurality of amplifier assemblies comprises:
- an amplifier;
- a body structure that is configured to support the amplifier, wherein the body structure comprises:
  - an inner surface and an opposing outer surface arranged such that the inner surface is positioned closer to the center axis than the outer surface; and
  - a first surface on which the amplifier is mounted and a second surface that opposes the first surface, wherein the first surface and the second surface form opposing sides of the body structure that are bounded by the inner surface and the outer surface;

and
- a heat sink that is entirely embedded within the body structure and a longitudinal dimension of the heat sink from the inner surface to the outer surface is greater than a dimension of the heat sink from the first surface to the second surface.

2. The spatial power-combining device of claim **1**, wherein the heat sink is provided closer to the first surface of the body structure than the second surface of the body structure.

3. The spatial power-combining device of claim **1**, wherein the heat sink extends within the body structure in a lateral direction relative to the first surface of the body structure.

4. The spatial power-combining device of claim **3**, wherein the heat sink extends in the lateral direction a distance that is greater than one or more peripheral edges of the amplifier.

5. The spatial power-combining device of claim **1**, wherein the heat sink comprises a material having a higher thermal conductivity than the body structure.

6. The spatial power-combining device of claim **1**, wherein the heat sink comprises one or more of a metal, a ceramic, and a polymer.

7. The spatial power-combining device of claim **1**, wherein the heat sink comprises one or more of a heat pipe, a thermal ground plane, and a phase change material.

8. The spatial power-combining device of claim **1**, wherein the heat sink forms two parallel opposing faces within the body structure.

9. The spatial power-combining device of claim **1**, wherein the heat sink forms a cross-sectional wedge shape.

10. The spatial power-combining device of claim **1**, wherein the body structure is formed by additive manufacturing.

11. A spatial power-combining device for modifying a signal comprising a plurality of amplifier assemblies radially arranged around a center axis, wherein each amplifier assembly of the plurality of amplifier assemblies comprises:
- an amplifier;
- a body structure that is configured to support the amplifier, wherein the body structure comprises:

an inner surface and an opposing outer surface arranged such that the inner surface is positioned closer to the center axis than the outer surface; and

a first surface on which the amplifier is mounted and a second surface that opposes the first surface, wherein the first surface and the second surface form opposing sides of the body structure that are bounded by the inner surface and the outer surface;

and

a heat sink that is partially embedded within the body structure, the heat sink extending in a lateral direction relative to the first surface of the body structure a distance that is greater than one or more peripheral edges of the amplifier.

12. The spatial power-combining device of claim **11**, wherein the heat sink is provided closer to the first surface of the body structure than the second surface of the body structure.

13. The spatial power-combining device of claim **11**, wherein the heat sink extends in the lateral direction to the outer surface of the body structure such that a peripheral edge of the heat sink is exposed at the outer surface.

14. The spatial power-combining device of claim **11**, wherein at least a portion of the heat sink is exposed at the first surface of the body structure.

15. The spatial power-combining device of claim **11**, wherein the heat sink comprises a material having a higher thermal conductivity than the body structure.

16. The spatial power-combining device of claim **11**, wherein the heat sink comprises one or more of a metal, a ceramic, and a polymer.

17. The spatial power-combining device of claim **11**, wherein the heat sink comprises one or more of a heat pipe, a thermal ground plane, and a phase change material.

18. The spatial power-combining device of claim **11**, wherein the heat sink forms two parallel opposing faces within the body structure.

19. The spatial power-combining device of claim **11**, wherein the heat sink forms a cross-sectional wedge shape.

20. The spatial power-combining device of claim **11**, wherein the body structure is formed by additive manufacturing.

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